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Electrical Conductivity Measurement of Nonideal Carbon Plasma

by George B. Vunni and Alan W. DeSilva

ARL-TR-4551 **August 2008**

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ARL-TR-4551 **August 2008**

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REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED (From - To)
August 2008	Final	30 September–30 May 2008

4. TITLE AND SUBTITLE
Electrical Conductivity Measurement of Nonideal Carbon Plasma

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
George B. Vunni and Alan W. DeSilva*

5d. PROJECT NUMBER
TSN06205

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRD-ARL-WM-TE
Aberdeen Proving Ground, MD 21005-5069

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-4551

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
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14. ABSTRACT
The electrical conductivity of carbon plasmas is measured in the range of densities from 0.16 solid density down to about 0.05 solid density and reported for values of internal energy ranging from 4 to 22 kJ/g. Plasmas are formed by rapid electrical discharge through thin graphite fibers immersed in a water bath. The pressure in the expanding plasma column is determined by a hydrodynamic model to describe the effect on the water surround. At constant internal energy per unit mass U, conductivity σ varies with specific volume V as $\sigma = V^{\alpha}$, where α is about 1.2 for $U < 6$ kJ/g , and rises to about 1.5 for $U = 22$ kJ/g.

15. SUBJECT TERMS
plasma, electrical conductivity, carbon, energy, temperature

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			George B. Vunni
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL	20	19b. TELEPHONE NUMBER (*Include area code*) (410) 278-3748

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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Acknowledgments

The authors wish to acknowledge Dr. Charles Hummer of the U.S. Army Research Laboratory (ARL) for making this collaboration possible between ARL and University of Maryland, College Park, and for helpful discussions on pulse power, plasma physics, wire explosion, and novel techniques of plasma diagnostics. It is always a great pleasure to thank Dr. John Powell of ARL for reviewing this report. This research was supported in part by funding from ORISE for postdoctoral research at ARL, under the contract no. W911QX04C0129. The authors gratefully acknowledge support from ARL for research collaboration with University of Maryland, College Park, under contract no. TCN06205.

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1. Introduction

A number of recent studies have been undertaken on exploding wire plasmas (*1–5*). The interest in these plasmas is related to sophisticated phenomena associated with their formation at high temperatures. Knowledge of material properties over a wide range of temperatures and pressures is important for several U.S. Army-related applications, such as electromagnetic armor, electromagnetic propulsion, electrical conduction in shaped charge jets, and plasma chemical physics. Thermophysical properties are also important for validating computer simulation codes such as ALEGRA (Arbitrary Lagrangian Eulerian General Research Application). ALEGRA is widely employed in the U.S. Army for studying dynamic material response of complex configurations. Past work has concentrated on investigating exploding metals; this report represents a first effort in the study of nonmetals.

Electrical conductivity of plasmas formed of nonmetals might be expected to show different characteristics from those of pure metal plasmas. Carbon is such a nonmetal in its normal state of graphite. Since graphite electrodes are widely used and carbon plasmas form necessarily whenever an arc is struck with such an electrode, a study of carbon conductivity may be of industrial, military, and basic scientific interest. Although the conductivity of dense metal plasmas has been extensively studied and reported (*1–10*), the conductivity of carbon in the plasma state has received less attention (*11*), perhaps due to the difficulty in preparing plasmas of carbon for study. This report studies the electrical conductivity of nearly pure carbon plasma for densities ranging from about 60% of solid density down to almost 2 orders of magnitude less.

Measurements of resistivity and specific heat of graphite reported in the literature show wide variations, depending on the sample preparation and configuration. In work reported previously (*1*), the electrical conductivity of dense metal plasmas was measured over densities ranging from near solid density down to about 1% of solid density. These measurements were made in plasmas created by rapid heating and vaporization of a wire sample in a water bath and yielded the conductivity as a function of density and temperature. The pressure and temperature were determined with the aid of SESAME-tabulated equation of state (EOS) tables. In this report the same method is used to create more or less pure carbon plasmas and to measure their conductivity. However, the conductivity results reported in this work do not depend on the use of tabulated EOS tables, and the data are presented as functions of internal energy and density.

2. Experimental Procedure

The form of carbon utilized in this study is a bundle of fine graphite fibers, termed a "tow" by the industry. The individual fiber is derived from a thread of polymerized acrylonitrile (PAN) that has been oxidized and then baked at a high temperature, "graphitized," turning it into nearly pure carbon. Such tows are intended for a number of uses where light, strong composite materials are desired. The tow used in this work was supplied by the HexCel Corporation, designated "AS4C-GP," and consists of a bundle of 3000 fine graphite fibers, each 6.9 μm in diameter, bound together with a small amount of sizing that is itself primarily carbon. The mass per unit length of the tow is 0.200 g/m, and using the total cross-sectional area occupied by fibers, we find the graphite density is 1.78 g/cm^3, compared with 2.25 g/cm^3 density of single crystal graphite (*11*). As supplied, the bundle has a flat rectangular cross section measuring about 1.49 mm in width and 0.12 mm in thickness, yielding a cross-sectional area of 0.178 mm^2, compared to the area obtained by summing the 3000 individual fiber cross sections, giving a total of 0.11 mm^2. Therefore, the fraction of the cross-sectional area occupied by carbon fiber in the tow is 62%, and the effective initial density of carbon is 1.098 g/cm^3. Note that geometrically, 62% is the result of close hexagonal packing of the individual fibers. The tow used in this study has a resistance of 1.3 ohm/cm, which leads to a room temperature conductivity of 7.0×10^4 S/m for the graphite fibers, compared to about 1.9×10^5 S/m for plane of pyrolytic graphite with a density of 2.1 g/cm^3 (*11*).

Measurements are made in a cylindrical aluminum chamber 15 cm deep and 30 cm in diameter (see figure 1). The fiber sample is clamped between an active electrode in the center of the chamber, and to a return electrode above, and has an overall length of 15 mm and a resistance of 2.1 ohms. In order to provide effective cylindrical symmetry before being clamped at the top electrode, the flat fiber is twisted through about three turns to form a nearly round bundle ~0.48 mm in diameter. The chamber is then filled with water. The fiber is rapidly heated and vaporized by current switched into it from a 1.88-μF capacitor, which may be charged to an initial voltage up to 20 kV. Vaporization occurs in about 1 μs. As the plasma formed expands, the water serves to impede the expansion so that a relatively uniform cylindrical plasma column exists within the plasma-water boundary. In previous work with metal plasmas, we have determined that the assumption that the plasma conditions within the boundary formed by the plasma-water interface are uniform is a good approximation. This follows from the observation that sound speed within the plasma is greater than the boundary expansion speed, so conditions within the boundaries may equalize rapidly.

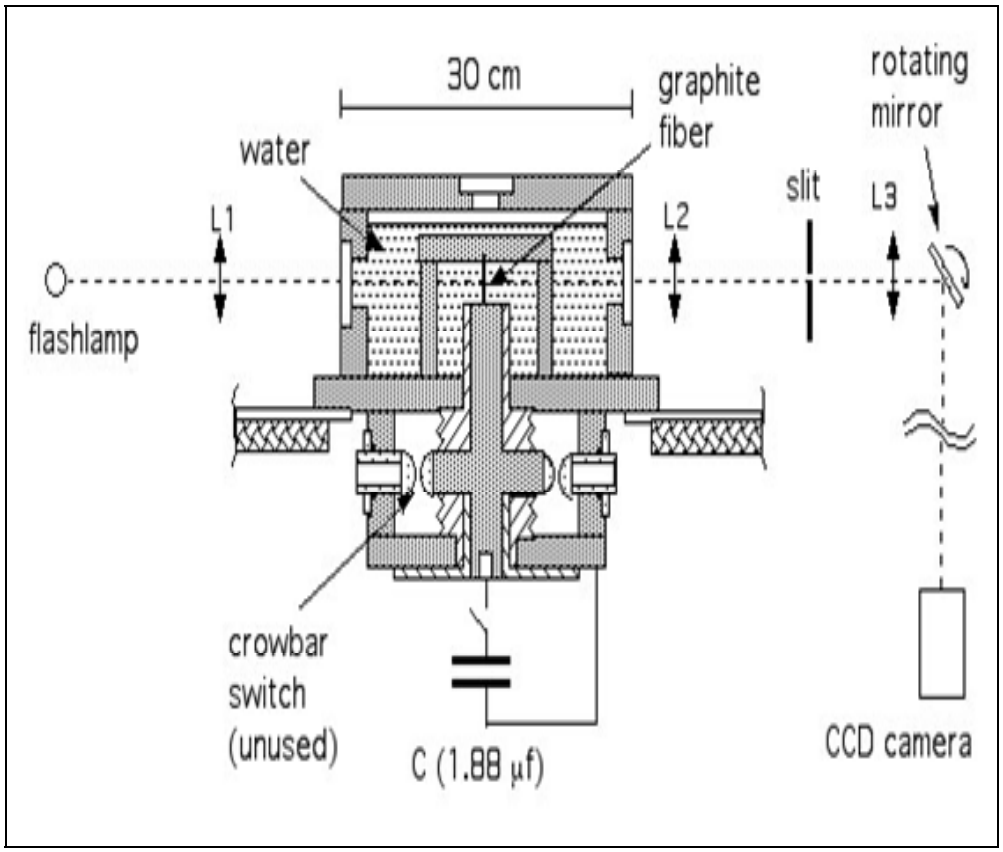

Figure 1. Schematic of discharge chamber used for exploding carbon graphite fiber.

3. Diagnostics

The voltage between the fiber ends is measured with a 670:1 high-voltage resistive divider, followed by a 25:1 further divider at the recording digital oscilloscope and a correction made in the software for the small reactive component. Current is measured with a Rogowski loop surrounding the active electrode inside the chamber, where the output is passively integrated with an RC integrator, and corrected in the analysis software for the slight error owing to the finite RC decay time. The rate of expansion of the plasma column is recorded with the aid of a rotating mirror streak camera. The plasma is backlighted by a xenon flashlamp and imaged on a narrow slit, with the plasma axis perpendicular to the slit. The light passing through the slit represents a thin slice across the column diameter about midway between the electrodes. Light from the slit passes to a rapidly rotating mirror and is then focused on an intensified CCD camera (figure 1). The result is an image showing the time history of the plasma column diameter in silhouette (figure 2),

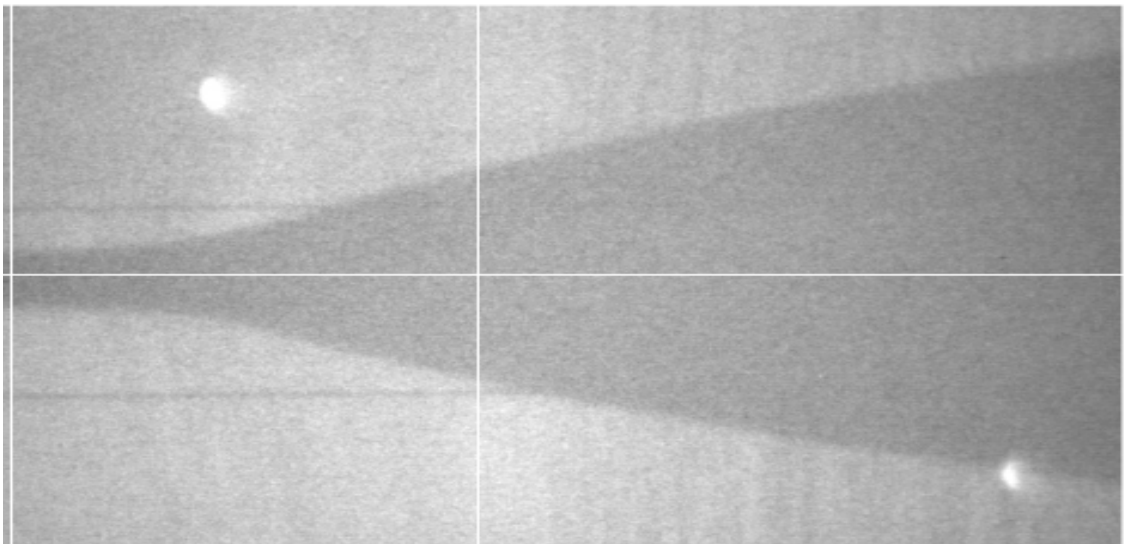

Figure 2. Streak image of a typical discharge. Timescale is determined from the two spots of light occurring at 2.54 μs and 13.57 μs after initiation of the discharge. The two horizontal lines are 1.56 mm apart.

The plasma-water interface is quite sharply defined for the first several μs, as shown by the streak camera images. A spatial reference on the image is provided by a pair of very thin wires stretched across the slit, appearing as a pair of dark lines on the image. A time reference is provided by a pair of spark gaps positioned just in front of the slit (on the flashlamp side), yielding a pair of light spots on the image when fired at known times.

4. Analysis of the Experimental Results

The primary recorded data are the voltage and current at 4-ns intervals and the column diameter measured from the streak image. The streak images are digitized to give column diameter as a function of time, and the measurements from the images are interpolated to produce a table of plasma diameter at the same 4-ns intervals. The current, voltage, and diameter data are input into an analysis program which steps through these data, tracking the development of column diameter, density, internal energy, and pressure (figure 3). A Lagrangian hydrodynamic model for the water relates the measured rate of radial expansion of the column to the pressure at the plasma-water interface. The energy expended by the plasma is then given as pdV where it is assumed that the pressure at the interface is equal to the pressure throughout the plasma column. The change in internal energy of the plasma in a single 4-ns step is the electrical energy input less the expansion energy $(VI - p\,dV)\,dt$. The column resistance R at each step is simply ε/I, and the conductivity is l/RA, where A is the instantaneous cross-sectional area of the column and l is its length, which is constant due to the massive electrodes. Following this analysis, we search through the data and select for plotting those times when the internal energy is within

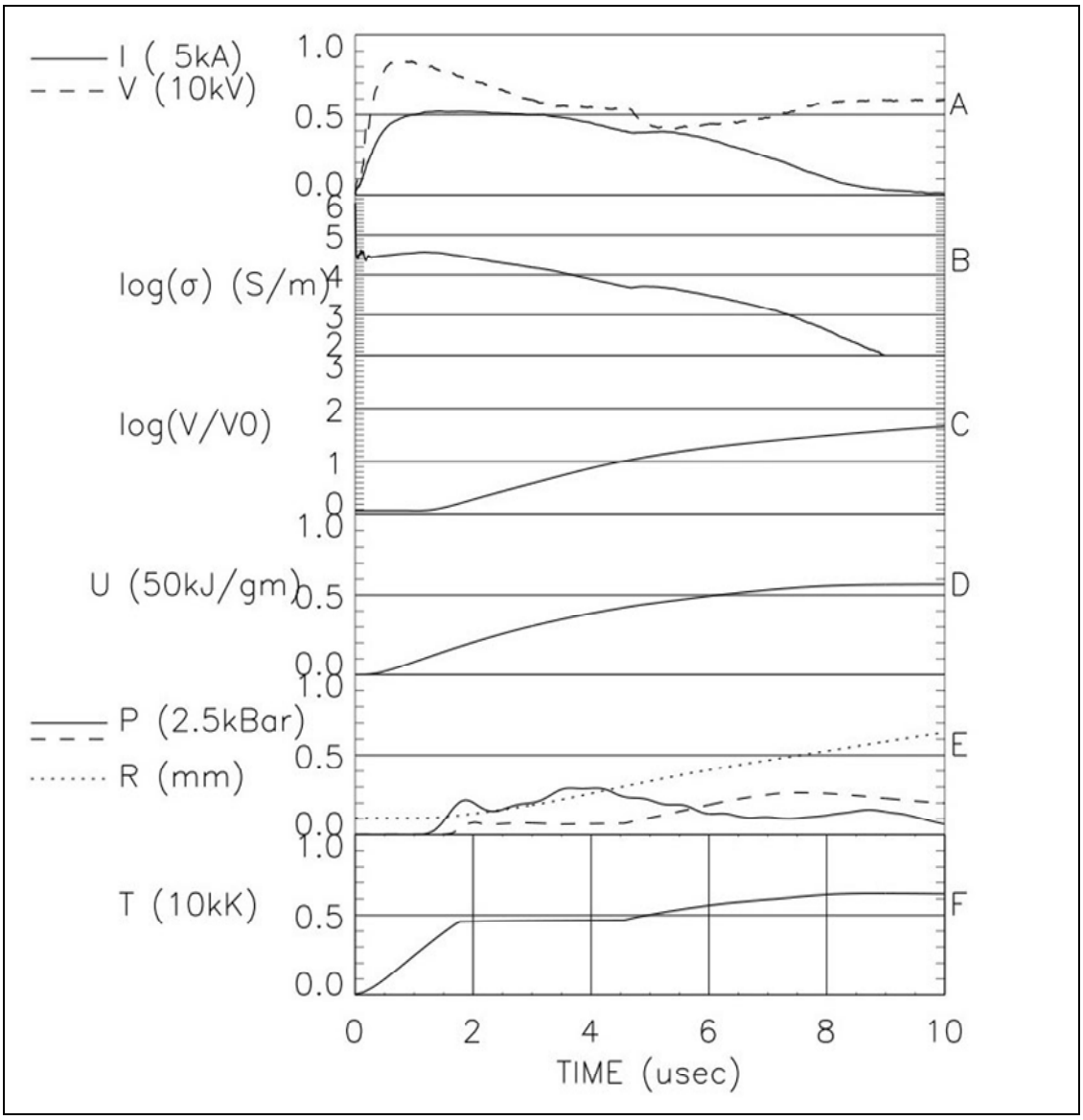

Figure 3. Time record of a shot with 2 ohms additional resistance in the discharge circuit and with the capacitor bank charged to 16 kV. Scale multipliers and units are shown at left.

a small range, some preselected value. In order to obtain data for a wide range of conditions, we may vary the series reactance in the external circuit and/or the voltage of the capacitor bank on successive discharges. Assembling such data from a large number of shots, we build up a picture of conductivity vs. density (or specific volume) and internal energy.

The analysis given previously differs from that used in our former work with metal samples in which the SESAME EOS database was a necessary part of the analysis. Using the present technique, we do not require the use of a tabulated EOS database to obtain the conductivity, but use it only to give an indication of the temperature.

5. Results and Discussion

Figure 3 shows the result of the analysis on a typical discharge. The measured data are the voltage and current, in window A, and the column radius taken from the streak image, shown in window E. All other curves are the result of the following calculations: B–conductivity (MKS units); C–ratio of specific volume to that of solid graphite; D–internal energy; E–solid line is pressure from the hydrodynamic model for water, dashed line is the pressure from SESAME, and the dotted line is the measured plasma column radius. Irregularities in the pressure trace are the result of small errors in digitizing the streak images; F–temperature from SESAME.

The time history shown in figure 3 is typical and shows that as the plasma expands, the column becomes nonconducting when the internal energy has risen to about 27 kJ/g and the plasma volume has increased by about a factor of about 40. If the current is increased by either reducing the series resistance in the circuit or by starting with a higher voltage on the capacitor bank, the column may become nonconducting rather suddenly; that point is still associated with internal energy of about 25 kJ/g.

Figure 4 shows the conductivity of carbon plasmas as a function of specific volume, at internal energy values ranging from 2 to 22 kJ/g. At the lowest values of internal energy shown, there has been little expansion of the column. The specific volume remains near its initial value of 5.62×10^{-4} m^3/kg, and the conductivity remains near the initial value of 7.0×10^4 S/m. As the plasma absorbs energy, the pressure increases and the column expands rapidly. Taking the results of a large number of discharges under various initial conditions, we observe that at constant energy, the conductivity diminishes as specific volume increases, the relationship approximated by $\sigma = (V / V_o)^{\alpha}$. At 2 kJ/g, α is ~1.2. As the internal energy increases, the exponent α grows to about 1.5 at U = 22 kJ/g. At higher values of internal energy, it does not appear to be possible to make a meaningful linear fit to the $\log V$ -$\log \sigma$ data. At these higher values of internal energy, it is impossible to obtain data for V / V_o close to unity because the energy input is not sufficiently fast for the plasma to arrive at high energy before significant expansion occurs.

The pattern of roughly linear decrease in $\log(\sigma)$ vs. $\log (V / V_o)$ at constant internal energy observed in the plots seems to hold until the internal energy reaches about 25 kJ/g and the specific volume has increased by a factor of about 10. When the bank voltage is low or the series resistance is high so that the peak current never gets above 5 kA, a finite conductivity may persist for even larger expansion of the column, up to V / V_o, as much as 30 (figure 4), but the internal energy still appears to be limited to about 25 kJ/g.

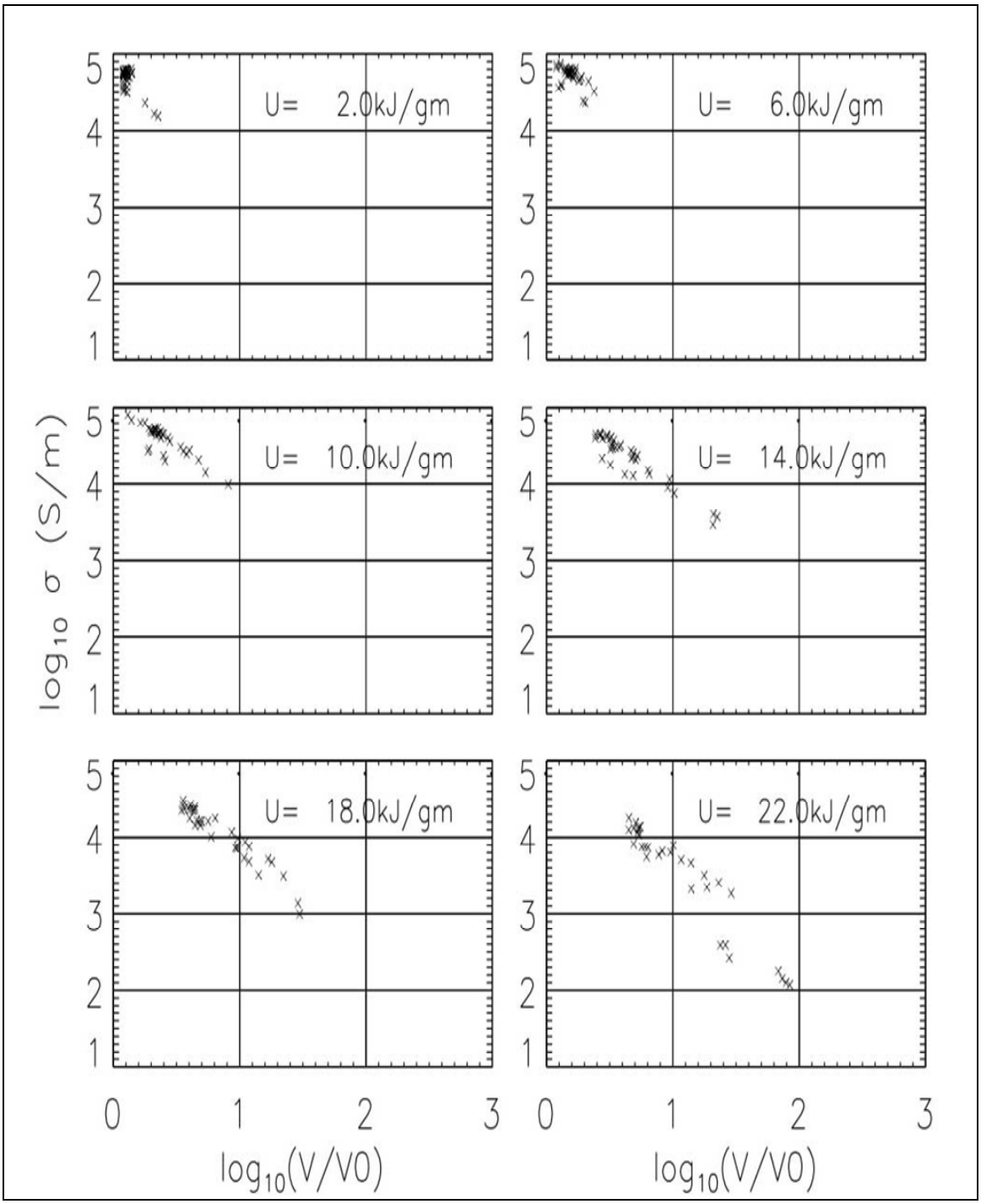

Figure 4. Conductivity vs. specific volume, at six different values of the internal energy density.

Figure 5 shows the development of the carbon conductivity in the early portion of the discharge, while the fiber is still in the solid state, for 14 discharges. As expected, the initial resistance of the fiber is about 2 ohms but the conductivity increases with heating until the internal energy has reached about 6 kJ/gm, in contrast to the behavior of metals where conductivity in the solid state decreases with temperature.

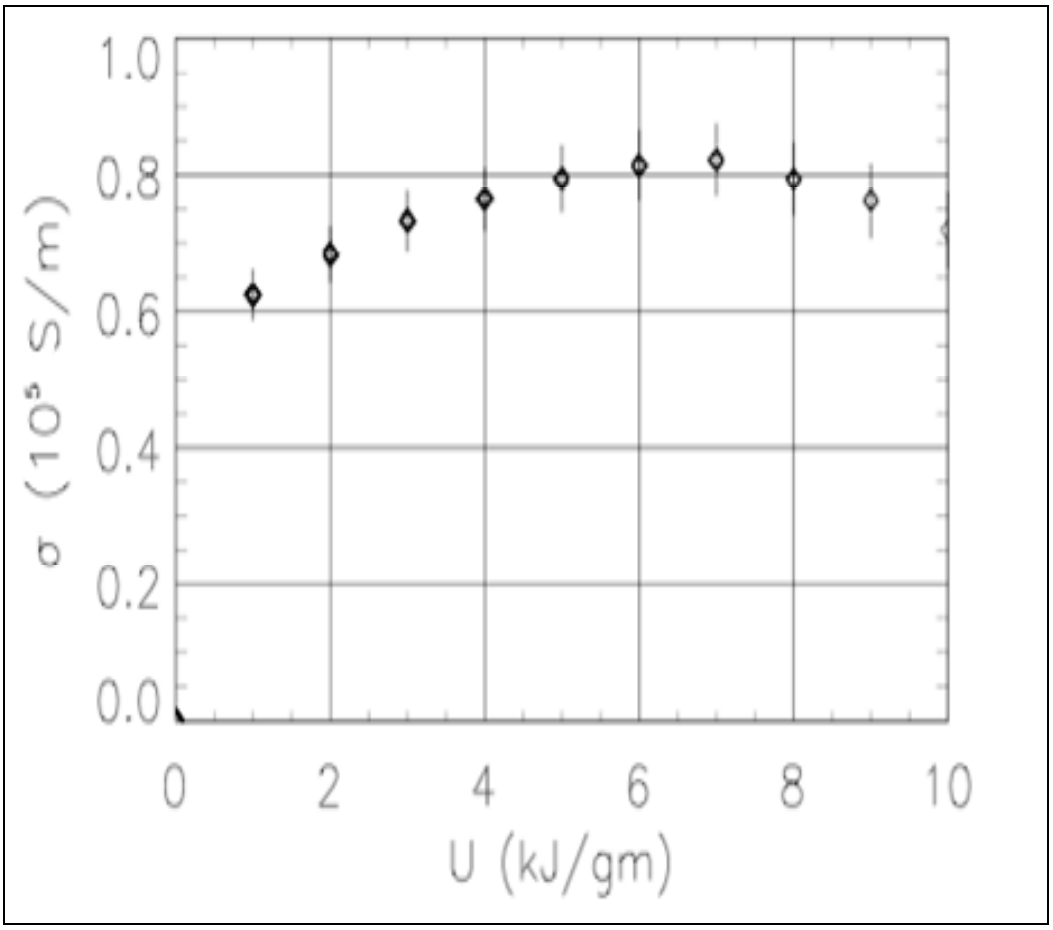

Figure 5. Conductivity of a carbon fiber bundle in the prevaporization phase, at $V / V_0 =$ 0.62. Error bars represent the standard error of the mean for 14 discharges.

In order to obtain an estimate of temperature, we can refer our data to the EOS for carbon-a7830 in the SESAME database. We have inserted our measurements for density and internal energy into the SESAME table and show the result for the different discharge conditions in figure 3. Since the SESAME tables also give the pressure for given density and energy, we also display the pressure taken from the carbon table. The measured pressures suffer from fluctuations that result from the errors in digitizing the streak images; this does not explain the differences from the SESAME-derived pressure. It seems likely that the SESAME tables fail to give an accurate relation between energy and pressure in this relatively low-energy region of parameter space.

The data of Korobenko et al. (*11*) are reported as functions of temperature in the 9–16 K range and V/V_0 in the 1-to-2 range. Our data are in terms of internal energy and specific volume. In order to compare, we need to appeal to the SESAME tables to find the energy densities associated with the temperatures in Korobenko et al. (*11*), and Haun et al. (*12*). The EOS tables indicate that over that whole range of temperatures and densities, the internal energies are greater than 50 kJ/g, well above the investigated energy densities. We have observed that the energy

density in the water-tamped explosions levels off at about 25 kJ/g. Attempts to drive the plasmas harder usually result in the formation of internal arcs that indicate nonuniform current density.

We see a large difference when we compare our results with those of Korobenko et al. (*11*). They heated cylindrical samples of very pure, highly grain-oriented graphite and found conductivity over 300× larger than in our observation. For the solid state, this may well be due to the known difference in resistivity, with direction of current flow relative to the grain orientation. However, after the sample reaches the liquid or vapor state, this can no longer account for the differences, which persist after vaporization.

6. Conclusion

We have been able to produce nearly pure carbon plasmas over a range of densities from about 60% of solid density down to about 0.05 solid density and measure the electrical conductivity for these plasmas. The primary measurements are the current through, and voltage along, the plasma column and streak images showing the time development of the column diameter. From these inputs and with aid of a Lagrangian hydrodynamic model for the water surrounding the plasma, we deduce the specific volume, internal energy, and pressure in the plasma. The variation of conductivity with specific volume at constant internal energy is less pronounced than it is for some of the metals we have studied. In a future report we will present contrasting data obtained in a similar manner for a number of metals.

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